Current instability and single-mode THz generation in ungated two-dimensional electron gas

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We analyze the current instability of the steady state with a direct current for an ungated two-dimensional(2D) electron layer for arbitrary current and the carrier scattering strength. We demonstrate the possibility of single-mode generator operating in terahertz frequency range.

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Recently, the interest in the plasma wave generation mechanism [1] in an ultrashort-channel field effect transistor (FET) has attracted much attention. The high-density 2D electron gas can be described by equations similar to the hydrodynamic equations for shallow water, resulting in the plasma wave generation [1]. Under the asymmetric boundary conditions with a fixed voltage at the source and fixed current at the drain lead to an instability of the steady state with a dc current. The plasma wave instability in short-channel FETs is very important for applications such as high-power sources and both the non-resonant[2]-[4] and resonant[5,6] detectors in the terahertz (THz) frequency range(see also [7]. Recently, the current instability and resulting plasma wave generation similar to that for field effect transistor shown to occur in an ungated 2D electron layer for asymmetrical boundary conditions [8].

In the present letter, we analyze the plasma wave instability for arbitrary current and the carrier scattering strength. We demonstrate the feasibility of single-mode generator operating in terahertz frequency range.

We will use the hydrodynamic model of weakly damped($\omega\tau \gg 1$, where ω is the plasma frequency, τ is the relevant collision time), incompressible charged-electron fluid placed in a rigid, neutralizing positive background. Moreover, we assume that the mean free path associated with electron-electron collisions is less than that related to scattering by phonons and impurities and than the device length. The behavior of the 2D fluid is described [8] by the Euler and the continuity one-dimensional equations:

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} = \frac{e}{m}\frac{\partial \phi}{\partial x} + \frac{v}{\tau} = 0, \qquad (1)$$

$$\frac{\partial n}{\partial t} + \frac{\partial (vn)}{\partial x} = 0. \qquad (2)$$

Here, n is the 2D electron density, v is the average electron flux velocity, m is the effective mass, $-e$ is the electronic charge and ϕ is the potential, therefore the electric field is $E = -\partial\phi/\partial x$.

Previous studies [1] correspond to dissipationless electrons when $\tau \to \infty$. At small currents the steady electron flow with a constant v_0, n_0 and $\phi_0 = 0$ shown to be unstable against small perturbations when the following boundary conditions are fulfilled:

$$n(0,t) = n_0, \qquad n(l,t)v(l,t) = j/We. \qquad (3)$$

Here $n(0,t)$ is the fixed 2DEG density at the device source($x = 0$), j is the fixed drain ($x = l$) current, and W is the 2D layer width. In the steady state, $n = n_0$ and $v = v_0 = j/(en_0W)$. These boundary conditions can be realized [8] by grounding the source by large capacitance presenting a short at plasma frequencies and by attaching the drain to the power supply via an inductance that presents an open circuit at the plasma frequencies.

We now search the solution of Eqs.(1) and (2) assuming finite carrier dissipation. In this case the steady-state corresponds to current carrying electron fluid with the constant density n_0(because of local quasi- neutrality of 2D fluid) and the constant average velocity $v_0 = \mu E = j/eWn_0$, where $\mu = e\tau/m$ is the carrier mobility. Thus, the steady-state potential ϕ_0 is linear downstream the electron flow. Let us now search the evolution of small perturbations $v_1, n_1, \phi_1 \sim \exp(-i\omega t + ikx)$ superimposed the steady state. Linearizing Eqs.(1) and (2) with respect to n_1, v_1 we find:

$$(\omega + i/\tau - kv_0)v_1 = -\frac{e}{m}k\phi_1,$$
$$(\omega - kv_0)n_1 = kn_0v_1. \qquad (4)$$

Neglecting finite-size effects, we explore the relation $\phi_1 = -\frac{2\pi e n_1}{|k|\epsilon}$ known for infinite ungated 2D electron layer. Here, ϵ is the background dielectric constant. Therefore, the dispersion equation yields:

$$(\omega + i/\tau - kv_0)(\omega - kv_0) = 2a\,|k|\,, \qquad (5)$$

where $a = \frac{\pi n_0 e^2}{\epsilon m}$. Introducing the dimensionless frequency $\omega^* = \frac{v_0}{a}\left(\omega + \frac{i}{2\tau}\right)$ we derive the dispersion relation for plasma wave propagating upstream k_+ and downstream k_- the current flow as follows:

$$k_\pm = \pm\frac{1 \pm \omega^* - \sqrt{1 \pm 2\omega^* - \frac{v_0^2}{4\tau^2 a^2}}}{v_0^2/a}. \qquad (6)$$

At small currents and zero-dissipation $1/\tau = 0$ Eq.(6) reproduce the dispersion relation $k_\pm = \pm\frac{\omega^2}{2a}\left(1 \mp \frac{\omega v_0}{a}\right)$ found in Ref.[8]. Searching the solution of Eq.(4) in the form $n_1 = A\exp(ik_+x) + B\exp(ik_-x)$, and, then use

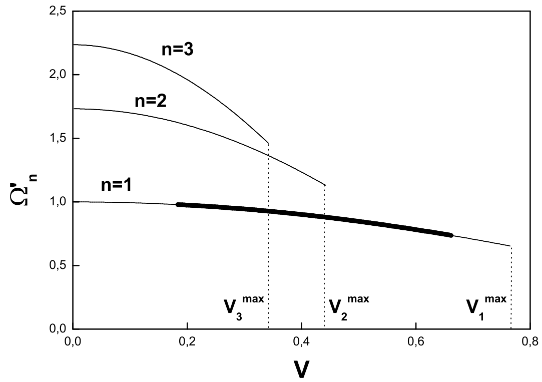

FIG. 1: Dimensionless frequency Ω'_n vs. dimensionless carrier velocity V for dissipationless electrons $\gamma = 0$ for $n = 1, 2, 3$ modes. Vertical dotted lines denote the cutoff V_n^{max} of the instability increment(see Fig.2). Bold line depicts the frequency of the single-mode generator at $\gamma_{min} = 0.055$

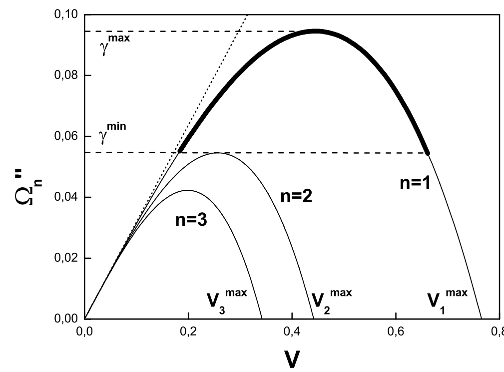

FIG. 2: Instability increment $\Omega''_n, n = 1, 2, 3$ vs. dimensionless carrier velocity V for zero-dissipation electrons $\gamma = 0$. The bold line depicts the positive part of the instability increment for single-mode generator when $\gamma = \gamma_{min} = 0.055$. Dotted line represents the zero-current asymptote $\omega'' = v_0/l$ found in Ref.[8]

the boundary conditions(see Eq.(3)) for zero ac potential at the source $n_1 = 0$ and zero ac current at the drain $n_0 v_1 + v_0 n_1 = 0$ we obtain

$$\frac{k_1}{k_2} = \exp\left[i(k_+ - k_-)l\right], \tag{7}$$

Equation (6) and (7) allow one to determine both the real and imaginary parts of the the complex frequency $\omega = \omega' + i\omega''$. A positive imaginary part $\omega'' > 0$ corresponds to instability. We now assume that for weakly damped 2D electrons the real part of the frequency is greater than both the imaginary part and the dissipation term $1/\tau$. Retaining the first order corrections in current $j \sim v_0$ in Eq.(6) and, then, separating the real and imaginary parts of the frequency we obtain:

$$\Omega'_n = \frac{1}{2V}\left[1 - \left(\frac{(2 - V^2(2n-1))^2 - 2}{2}\right)^2\right]^{1/2},$$
$$\Omega''_n = \frac{V}{\pi}\frac{\sqrt{1 - 4(\Omega'_n V)^2}}{\sqrt{1 - 2\Omega'_n V} - \sqrt{1 - 2\Omega'_n V}} \ln|R_s R_d| - \gamma,$$
$$R_s = -1, R_d = \frac{1 - \Omega'_n V - \sqrt{1 - 2\Omega'_n V}}{1 + \Omega'_n V - \sqrt{1 - 2\Omega'_n V}}, \tag{8}$$

where we introduced the dimensionless frequency $\Omega = \omega\sqrt{\frac{l}{\pi a}}$, carrier velocity $V = v_0\sqrt{\frac{\pi}{al}}$ and the instability damping strength $\gamma = \frac{1}{2\tau}\sqrt{\frac{l}{\pi a}}$. Then, R_s, R_d are the density amplitude reflection coefficients from the source and drain boundaries, so that the product $R_s R_d$ denotes the instability gain factor. Note that for small currents $V \to 0$ Eq.(8) describes the discreet frequency spectrum $\omega'_n = \sqrt{\pi a(2n-1)/l}$ and mode-independent instability increment $\omega'' = v_0/l - 1/2\tau$ reported in Ref.[8].

The most intriguing result of the present paper concerns the current dependence of Ω'_n, Ω''_n. In order to analyze the essential features of the plasma wave instability, we first consider zero-dissipation electrons when $\gamma = 0$. In Fig.1,2 we plot the current dependence of the frequency and the instability increment for the proper mode $n = 1$ and the high-order harmonics $n = 2, 3$. Each mode is characterized by its own increment which is positive within a certain range of currents, i.e. when $0 < V < V_n^{max} = \sqrt{\frac{2-\sqrt{2}}{2n-1}}$. In Fig.1 we represent the $n = 1, 2, 3$ mode frequency within the respective range of currents. Note that the higher the mode index n the narrower the n-th mode instability range. Actually, at $V = V_n^{max}$ the n-th mode increment disappears because the related group velocity of the upstream plasma wave $d\omega/dk_-$ vanishes(see Eq.6)). Its worthwhile to mention that at $V > V_2^{max} = 0.44$ the only first mode remains unstable, hence the device may operate as a single-mode generator.

In presence of finite dissipation the all modes are damped identically(i.e. $\gamma = const$). Thus, one can find the instability threshold for n-th mode as $\Omega''_n = 0$. With the help of Fig.2 we find the condition when the higher than the first mode are suppressed:

$$0.055 = \gamma^{min} < \gamma < \gamma^{max} = 0.095,$$
$$0.183 < V < 0.661 \tag{9}$$

The instability is totally suppressed when $\gamma > \gamma^{max}$. The frequency range of the single-mode generator for $\gamma = \gamma^{min}$ is represented by the bold line in Fig.1. Using Eq.(9) we now estimate the device parameters required for observation of the single-mode plasma wave generation. For $n = 10^{12}\text{cm}^{-2}$ InGaAs based(m=$0.042 m_e$) 2D layer length $l = 1\mu$m we obtain the required range of 2D carrier mobility as 3.2×10^4 cm^2/Vs$< \mu < 5.5 \times 10^4$

cm^2/Vs. When $\gamma = \gamma^{min}$, the single-mode generator output frequency and required carrier velocity fall in the range 5.0THz$< \omega' <$ 6.8THz and $4 \times 10^5 < v_0 < 1.4 \times 10^6$cm/s respectively.

In conclusion we found the plasma wave instability for arbitrary current and the carrier scattering strength. We demonstrate the possibility of single-mode generator operating in terahertz frequency range.

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